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Damage assessment in multiple-girder composite bridge using vibration characteristics

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Abstract

This paper uses dynamic computer simulation techniques to apply a procedure using vibration-based methods for damage assessment in multiple-girder composite bridge. In addition to changes in natural frequencies, this multi-criteria procedure incorporates two methods, namely the modal flexibility and the modal strain energy method. Using the numerically simulated modal data obtained through finite element analysis software, algorithms based on modal flexibility and modal strain energy change before and after damage are obtained and used as the indices for the assessment of structural health state. The feasibility and capability of the approach is demonstrated through numerical studies of proposed structure with six damage scenarios. It is concluded that the modal strain energy method is competent for application on multiple-girder composite bridge, as evidenced through the example treated in this paper.

Keywords: bridges; damage detection; finite element method; modal analysis; flexibility; strain energy

Introduction

Bridges are normally designed to have long life spans. Changes in load characteristics, deterioration with age, environmental influences and random actions may cause local or global damage to structures. Continuous health monitoring of structures will enable the early identification of distress and allow appropriate retrofitting to prevent potential sudden structural failures. In recent times, structural health monitoring (SHM) has attracted much attention in both research and development. SHM defined by Housner et al. (1997) refers to the use of in-situ, continuous or regular (routine) measurement and analyses of key structural and environmental parameters under operating conditions, for the purpose of warning impending abnormal states or accidents at an early stage to avoid casualties as well as giving maintenance and rehabilitation advice. SHM encompasses both local and global methods of damage identification (Zapico and Gonzalez 2006). In the local case, the assessment of the state of a structure is done either by direct visual inspection or using experimental techniques such as acoustic emission, ultrasonic, magnetic particle inspection, radiography and eddy current. A characteristic of all these techniques is that their application requires a prior localization of the damaged zones. The limitations of the local methodologies can be overcome by using vibration-based (VB) methods, which give a global damage assessment. Health monitoring techniques based on processing vibration measurements basically handle two types of characteristics: the structural parameters (mass, stiffness and damping) and the modal parameters (modal frequencies, associated damping values and mode shapes). As the dynamic characteristics of a structure, namely natural frequencies and mode shapes are known to be functions of its stiffness and mass distribution, variations in modal frequencies and mode shapes can be an effective indication of structural deterioration. Deterioration of a structure results in a reduction of its stiffness which causes the change in its dynamics characteristics. Thus, damage state of a structure can be inferred from the changes in its vibration characteristics (Doebling et al. 1996). Usually there are four different levels of damage assessment (Rytter 1993): damage detection (Level 1), damage localization (Level 2), damage quantification (Level 3), and predication of the acceptable load level and of the remaining service life of the damaged structure (Level 4). The amount of literature is quite large for treating single damage scenarios, but limited for multiple damage scenarios. Also existing methods are based on a single criterion and may not be useful in several realistic situations. There is thus a need for a more comprehensive method of damage identification in structures. In this study, the modal flexibility and modal strain energy methods are chosen as their corresponding algorithms can be applied to both beam and plate elements. The advantage of using modal flexibility method is that the flexibility matrix is sensitive to changes in the lower-frequency modes of the structures due to the inverse relationship to the square of the natural frequencies. Therefore, a good estimate of the flexibility can be made with the inclusion of the first few frequencies and their associated mode shapes. The advantage of using modal strain energy method is that only measured mode shapes are required in the damage identification without knowledge of the complete stiffness and mass matrices of the structure. Only the mode shapes of the first few modes and their corresponding derivatives are required in this proposed algorithm for accurate damage localization.

Theory

Modal flexibility matrix

The modal flexibility matrix includes the influence of both the mode shapes and the natural frequencies. It is defined as the accumulation of the contributions from all available mode shapes and corresponding natural frequencies. The modal flexibility matrix associated with the referenced degrees of freedom can be established from Eq. (1) found in Huth et al. 2005.

$$[F] = [\phi][1/\omega^2][\phi]^T \qquad 1$$

where $[F]$ is the modal flexibility matrix; $[\phi]$ is the mass normalized modal vectors; and $[1/\omega^2]$ is a diagonal matrix containing the reciprocal of the square of natural frequencies in ascending order. The modal contribution to the flexibility matrix decreases as the frequency increases, i.e., the flexibility matrix converges rapidly with increasing values of frequency. From only a few of the lower frequency modes, therefore, a good estimate of the flexibility can be made. The change in the flexibility matrix $\Delta[F]$ due to structural deterioration is given by

$$\Delta[F] = [F^d] - [F^h] \qquad 2$$

where the index 'h' and 'd' refer to the healthy and damaged state respectively. Theoretically, structural deterioration reduces stiffness and increases flexibility. Increase in structural flexibility can therefore serve as a good indicator of the degree of structural deterioration.

Modal strain energy based damage index

The strain energy U of a Bernoulli-Euler beam is given as follows:

$$U = \int \frac{EI}{2}\left(\frac{d^2 y}{dx^2}\right)^2 dx \qquad 3$$

where x is the distance measured along the length of the beam, y is the vertical deflection, EI is the flexural rigidity of the cross section and d^2y/dx^2 is the curvature of the deformed beam.

Deterioration of a structure results in a reduction of its stiffness which causes the changes in modal strain energy. The damage localization method is based on the relative differences in modal strain energy between an undamaged and damaged structure. Information required in the identification are the measured mode shapes only without knowledge of the complete stiffness and mass matrices of the structure. The equation used to calculate the damage index β_{ji} for the jth element and i mode of a beam is given by

$$\beta_{ji} = \frac{\left(\int_j [\phi_i''^*(x)]^2 dx + \int_0^L [\phi_i''^*(x)]^2 dx\right)\int_0^L [\phi_i''(x)]^2 dx}{\left(\int_j [\phi_i''(x)]^2 dx + \int_0^L [\phi_i''(x)]^2 dx\right)\int_0^L [\phi_i''^*(x)]^2 dx} \qquad 4$$

To account for all available modes, a single indicator for each location along the beam is given by

$$\beta_j = \frac{\sum_{i=1}^{NM} Num_{ji}}{\sum_{i=1}^{NM} Denom_{ji}} \qquad 5$$

where Num_{ji} is the numerator of β_{ji} and $Denom_{ji}$ is the denominator of β_{ji} in Eq. (4).The complete derivation of the damage index for beam and plate are given in references (Stubbs et al. 1995 and Cornwell et al. 1999).

Method

As a single damage indicator is not reliable, especially in the case of multiple damages, the multi-criteria approach which incorporates (1) change of frequency Δf , (2) change of flexibility matrix ΔF and (3) change of modal strain energy are used in the damage assessment. Initially the multiple-girder composite bridge is developed as a finite element (FE) model and its modal response is obtained using the FE software SAP2000. Additional FE models with six damage scenarios are generated for investigation. The first five modes of the primary modal parameters (i.e., natural frequencies & mode shapes), before and after damage in six damage scenarios are extracted from the results of the FE analysis. These parameters are then used to determine the change of modal flexibility and the change of modal strain energy and thereby assess the structural health. The peak values of the damage parameter above the defined damage limit in each method indicate the corresponding simulated damage location. Detailed descriptions of the finite element model and simulated damage cases of a multiple-girder composite bridge are described below.

Finite element modelling of multiple-girder composite bridge

A multiple-girder composite bridge as shown in Figure 1 is treated in this study. The superstructure used as the basis for the investigation is a zero-skew, single span with 12.8m wide concrete deck spanning 30m. The deck is supported by four welded-steel plate girders which are I-section assembled of flange and web plates. The geometric and material properties of the multiple-girder composite bridge are listed in Table 1. Cross bracing at spacing of 2m is provided between girders. Both bridge deck and girders are modelled as shell elements while steel diagonal bracings are modelled as truss elements. The deck and each girder are divided into 480 & 240 elements respectively. Four girders having the same span are simply supported at their ends and rotations about all 3 axes are allowed in order to simulate the desired boundary conditions.

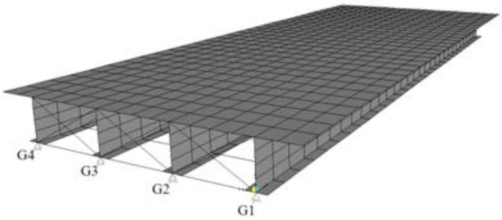
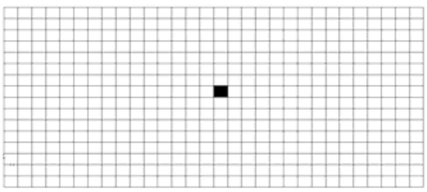


Figure 1. Isometric view of FE model with numbering system on girders

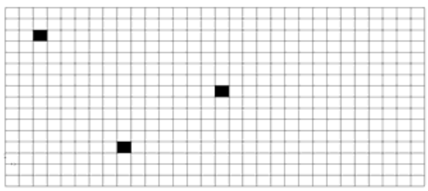
Table 1. Geometric and material properties of deck and girders

Flexural member	Deck (2D)	Girder (2D)
Element type	Shell	Shell
Material	Concrete	Steel
Length	30 m	30 m
Width	12.8 m	0.02 m
Depth	0.4 m	1.75 m
Poisson's ratio	0.2	0.3
Mass density	2400 kg/m^3	7800 kg/m^3
Modulus of elasticity	24 GPa	200 GPa

A total of six damage cases are investigated for the damage identification on bridge. The first two damage cases involve deck damage and the last four cases involve girder(s) damage as shown in Figures 2 & 3 respectively. Damage on deck and girder are simulated either by reducing the elastic modulus (E) of selected elements (0.5E) or removing the selected elements. In damage cases D1 & D2 as shown in Figures 2(a) & (b), a single and three damaged elements are simulated on the deck respectively. In damage case D3 as shown in Figure 3(a), a selected element with the size of 1000mm x 400mm x 20mm is removed from the bottom flange of the girder (G1) to simulate the damage. In damage cases D4-D6 as shown in Figures 3(b)-(d), damaged elements are simulated on the web of girders at different locations. It is assumed that linear behaviour of bridge occurs in all damage cases. The nonlinear effects associated with the crack are not studied in this investigation.

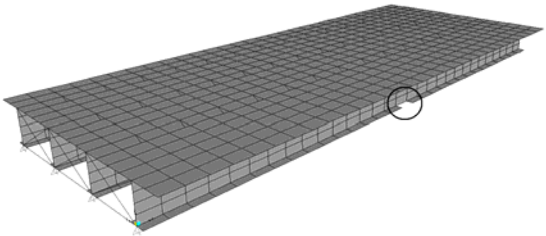


(a) D1 - Deck (reduced stiffness 0.5E)

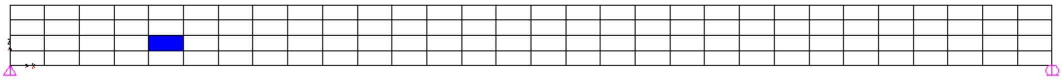


(b) D2 - Deck (0.5E)

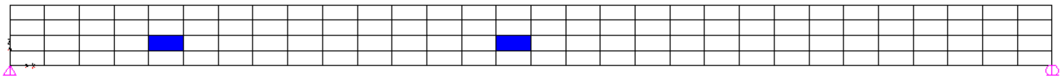
Figure 2. Damage cases (D1-D2) on deck.



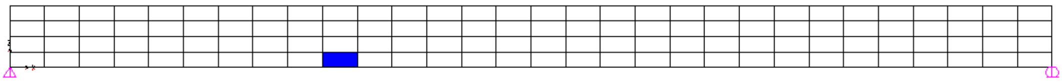
(a) D3 - Damage on bottom flange of G1 at mid-span



(b) D4 - Web of G2 (0.5E)

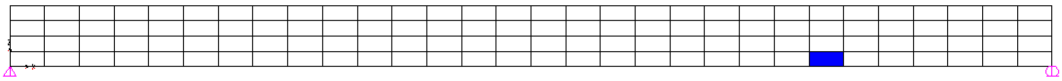


Web of G2 (0.5E)

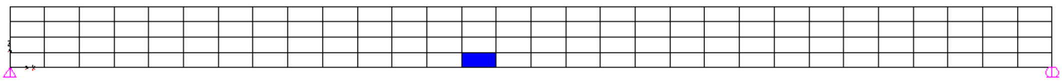


Web of G4 (0.5E)

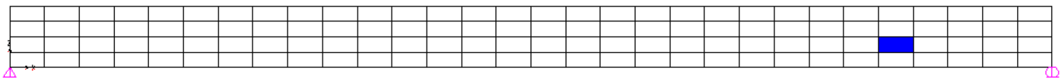
(c) D5



Web of G1 (0.5E)



Web of G2 (0.5E)



Web of G3 (0.5E)

(d) D6

Figure 3. Damage cases (D3-D6) on girders

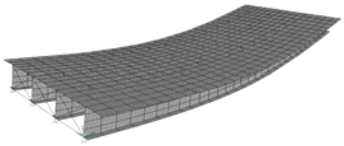
Results and discussions

Frequency change

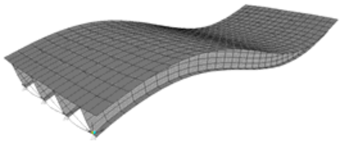
The natural frequencies of the first five modes of multiple-girder composite bridge before and after damage in six scenarios obtained from the FE analysis results are shown in Table 2. Percentage changes in the natural frequencies between the undamaged and damaged conditions are listed within brackets. It is observed that the presence of damage in multiple-girder composite bridge causes a decrease in the natural frequencies in all damage cases, with very few exceptions. There is no change of frequency for some modes (e.g. 2nd mode in damage case D4) because the damage elements are located at the nodes of vibration modes and hence have no influence on the corresponding natural frequencies. The five undamaged vibration mode shapes are illustrated in Figure 4. It appears that the dynamic behaviour of the bridge is governed by vertical bending modes, coupled with torsional modes, in the frequency range of 3 - 15 Hz. The fundamental mode is the vertical bending mode of the deck and girders which corresponds to a natural frequency of 3.75 Hz. The second vertical bending mode appears in mode 4 with natural frequency of 12.55 Hz. In mode 2, 3 & 5, it can be seen that they all involve coupled bending and torsional vibration of deck and girders.

Table 2. Natural frequencies from FEM for multiple-girder composite bridges
(Percentage changes wrt to the undamaged conditions are listed within brackets)

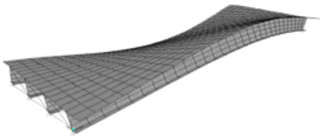
Situation		Mode 1 f_1 (Hz)	Mode 2 f_2 (Hz)	Mode 3 f_3 (Hz)	Mode 4 f_4 (Hz)	Mode 5 f_5 (Hz)
Original		3.75	5.02	12.31	12.55	14.48
Deck damage	D1	3.73 (-0.42)	5.01 (-0.03)	12.28 (-0.24)	12.54 (-0.06)	14.48 (0.01)
	D2	3.72 (-0.73)	5.00 (-0.24)	12.22 (-0.72)	12.49 (-0.47)	14.40 (-0.59)
Girder(s) damage	D3	3.72 (-0.68)	5.00 (-0.40)	12.30 (-0.11)	12.55 (-0.01)	14.48 (0.00)
	D4	3.75 (-0.01)	5.02 (0.00)	12.31 (0.00)	12.55 (-0.02)	14.48 (-0.01)
	D5	3.74 (-0.07)	5.02 (-0.03)	12.31(-0.01)	12.54 (-0.10)	14.47 (-0.05)
	D6	3.74 (-0.09)	5.01 (-0.04)	12.31 (-0.02)	12.54 (-0.07)	14.47 (-0.06)



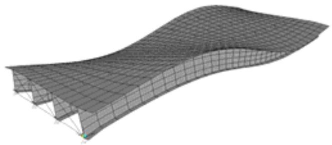
(a) Mode 1, f_1=3.75Hz



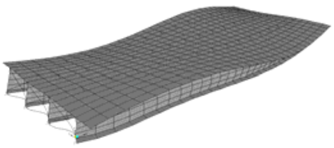
(d) Mode 4, f_4=12.55Hz



(b) Mode 2, f_2=5.02Hz



(e) Mode 5, f_5=14.48Hz



(c) Mode 3, f_3=12.31Hz

Figure 4. First five vibration modes of FE model.

Modal flexibility change (MFC)

The first five natural frequencies and associated mode shapes obtained from the eigenvalue analysis are used to calculate the MFC. Plots of MFC in deck for damage cases D1 & D2 are shown in Figures 5(a) & (b). The peak values of the plots indicate the damage locations on deck. In Figure 5(a), there is a peak at the mid-span, which conforms well with the damage case D1. In Figure 5(b), it is noted that the peaks in the plots do not match well with the corresponding damage in multiple locations. Therefore, it is concluded that MFC is only able to detect single deck damage, and it fails to detect multiple deck damages on multiple-girder composite bridge. Plots of MFC on deck for damage case D3, which pertain to girder damage (only) are shown in Figure 5(c). As expected, there are no distinguishing peak(s) across the intact deck. MFC in the deck for the other girder damage cases (D4, D5 and D6) are not shown as they draw the same conclusion as in damage case D3.

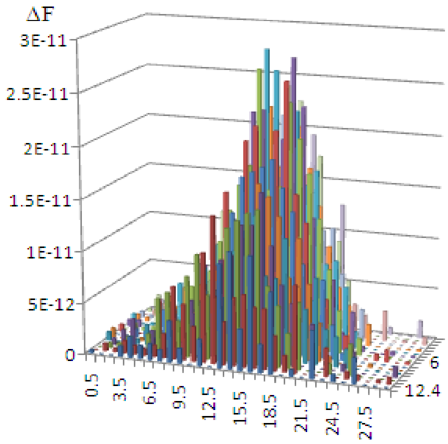
The plots of MFC along the four-girders for damage cases D1, D5 and D6 are shown in Figure 6. It is found that the plots do not provide any information for localization of damage, which means that MFC is not feasible for application on multiple-girder composite bridge.

Modal strain energy change (MSEC)

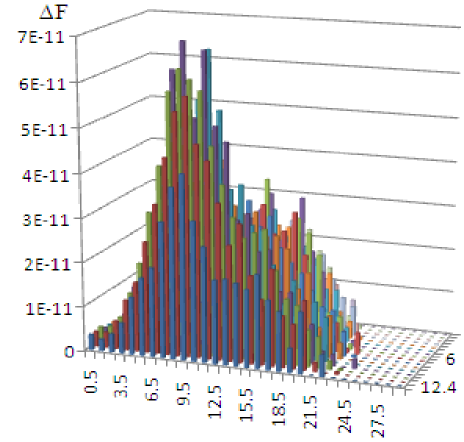
The first five mode shapes obtained from the eigenvalue analysis are used to calculate the MSEC (β). Plots of MSEC on deck for damage cases D1 & D2 are shown in Figures. 5(d) & (e). The peak values of the plots indicate the location of damage on the deck. In Figure 5(d), there is a distinct peak at the mid-span, which conforms well with the damage case D1. In Figure 5(e) there are three un-equal peaks which correspond to three damaged elements on the deck in damage case D2. It is concluded that the MSEC method is able to detect and locate damage zones on deck precisely in all deck damage cases. Figure 5(f) shows the MSEC in the deck when there is damage only in the girders. As expected, there are no distinguishing peak(s) in the plots of MSEC, as the plots are randomly distributed across the intact deck. It is also noted that the MSEC value in this figure shown in an enlarged scale are much smaller than those in Figures. 5(d) & (e).

The plots of MSEC along four girders for damage cases D1, D5 & D6 are shown in Figures 6(d)-(f). It can be seen that the plots for the undamaged girders in Figure 6(d), corresponding to deck damage case D1 oscillate in a range of 0.995 - 1.005 about the base line value of 1 and that the peaks in these curves have smaller values than those corresponding to the girder damage cases D5 & D6. The latter curves in Figures 6(e)-(f) for the damaged girders oscillate in a comparatively larger range of 0.99 – 1.015 about the base line value of 1. It is clearly evident that these figures, corresponding to girder damage cases D5 & D6 have distinct peaks (β over 1.005) at the damage locations. In damage case D5, there should be a total of three distinct peaks (β over 1.005) in the plots corresponding to girders damages. However, it is noted that the MSEC curve corresponding to this case obtains two peaks only, and one peak is missed.

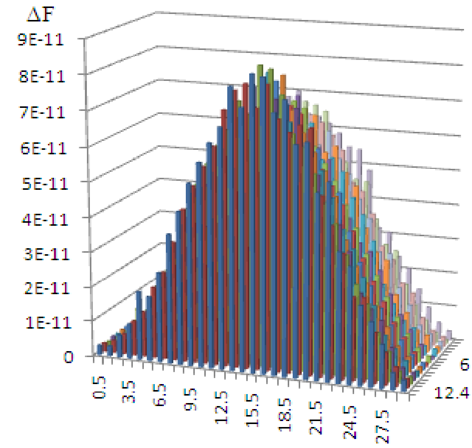
A total of 24 MSEC curves corresponding to damaged and undamaged girders for all damage cases are plotted in Figure 7 for comparison of amplitude. It is observed that the damaged girders have higher maximum amplitudes compared to the undamaged girders at corresponding damage location. Due to this fact, a damage limit on the change of modal strain energy is defined at 1.005 in order to locate all damages on the girders. From the observation, there should be seven peaks in the graph to be plotted. However, it is found that one has been missed in a girder (G4) in damage case D5. Overall, the results show that the modal strain energy method is competent to locate the damaged elements in both bridge deck and girders.



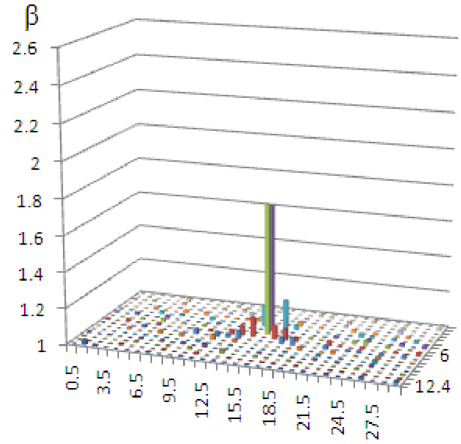
(a) D1



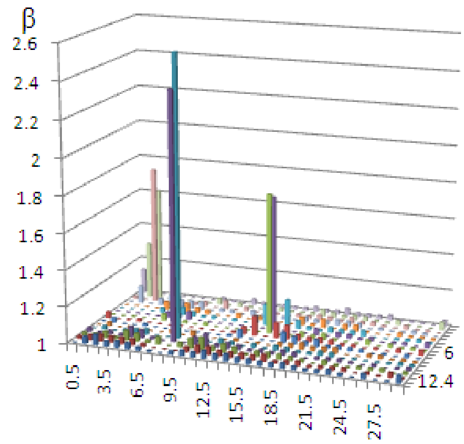
(b) D2



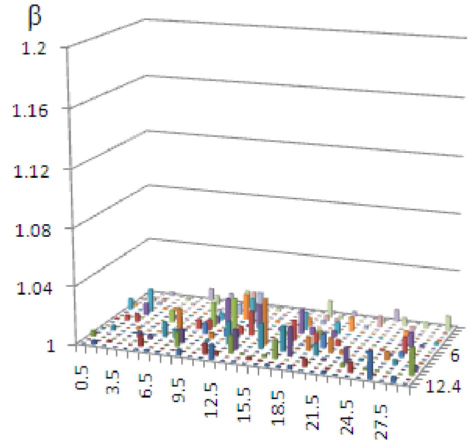
(c) D3



(d) D1



(e) D2



(f) D3

Figure 5. Modal flexibility change (left) & Modal strain energy based damage index (right) on deck.

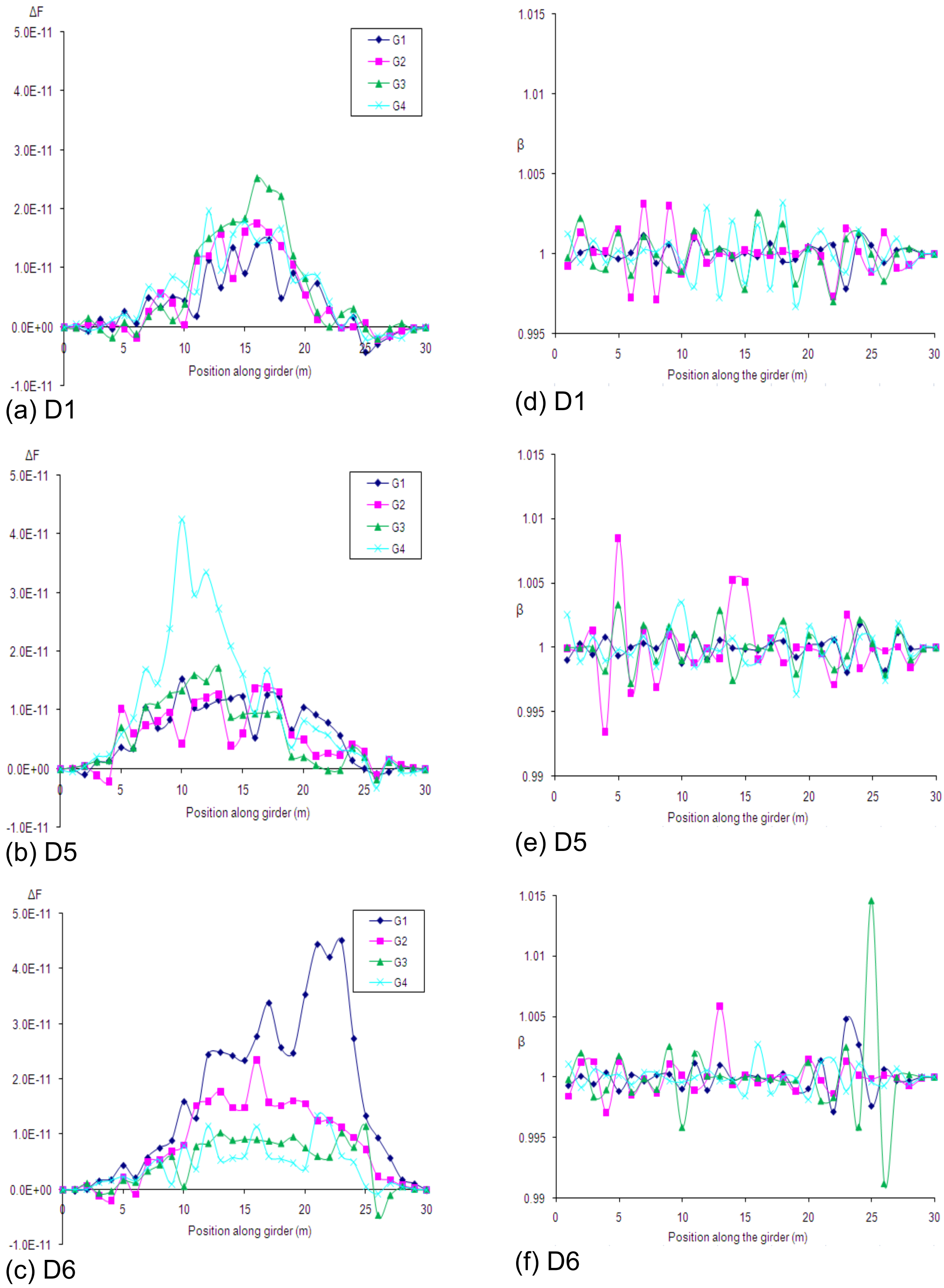


Figure 6. Modal flexibility change (left) & Modal strain energy based damage index (right) on girders

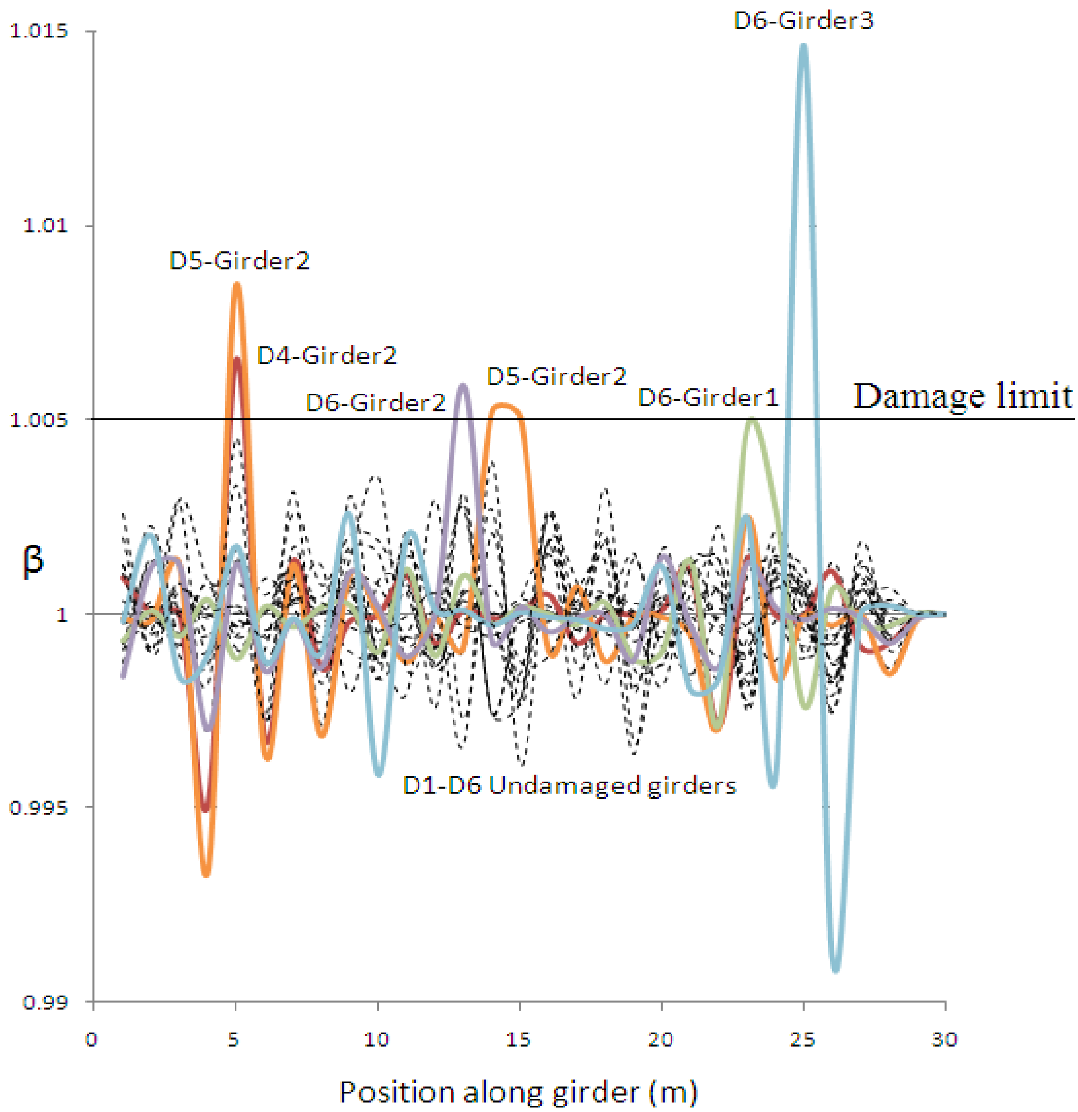


Figure 7. Relationship between modal strain energy based damage index and structural state of girders.

Conclusions

In the example of single-span multiple-girder composite bridge, three types of damage severity including flexural stiffness reduction of 50% on the deck, 50% on the web of girder and also removing element with size of 1000mm x 400mm x 20mm from the bottom flange of girder are investigated. It is found that the MSEC shows promise for detection of deck and girder damage. On the contrary, MFC is failure to detect damage on either deck or girders. Comparing between two methods, it is concluded that MSEC is suitable for application on multiple-girder composite bridge, while MFC is not.

Acknowledgements

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